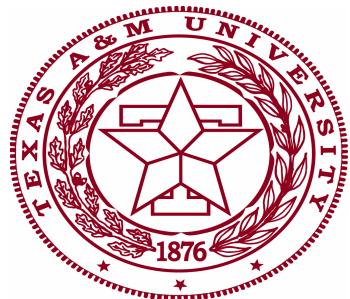


Azimuthal Anisotropy of High- p_T Direct Photons and Neutral pions at RHIC and LHC

Ahmed M. Hamed
Texas A&M University
University of Mississippi
Higher Colleges of Technology

11th International Workshop on High- p_T
Physics in the RHIC & LHC Era



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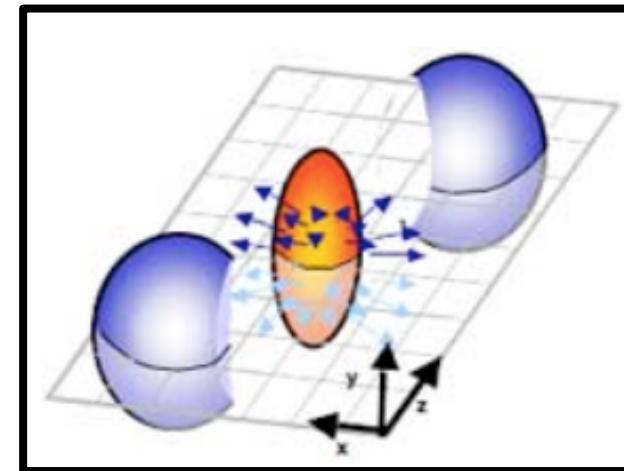
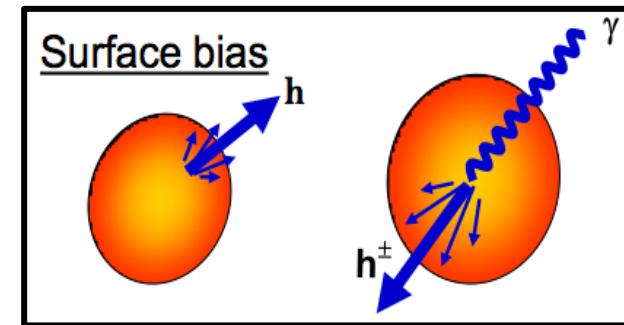
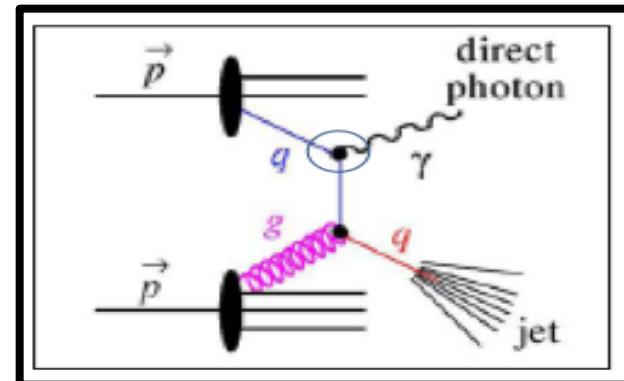
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Motivation: Parton Energy Loss in QGP

- Energy loss: *parton initial energy, path length, color factor, quark flavor, medium properties*
- EM interacting particles “high- p_T photons”: uniform hard scattering vertex in the QCD medium

* Reaction plane ($\Delta\phi$):
Azimuthal anisotropy of π^0 and γ

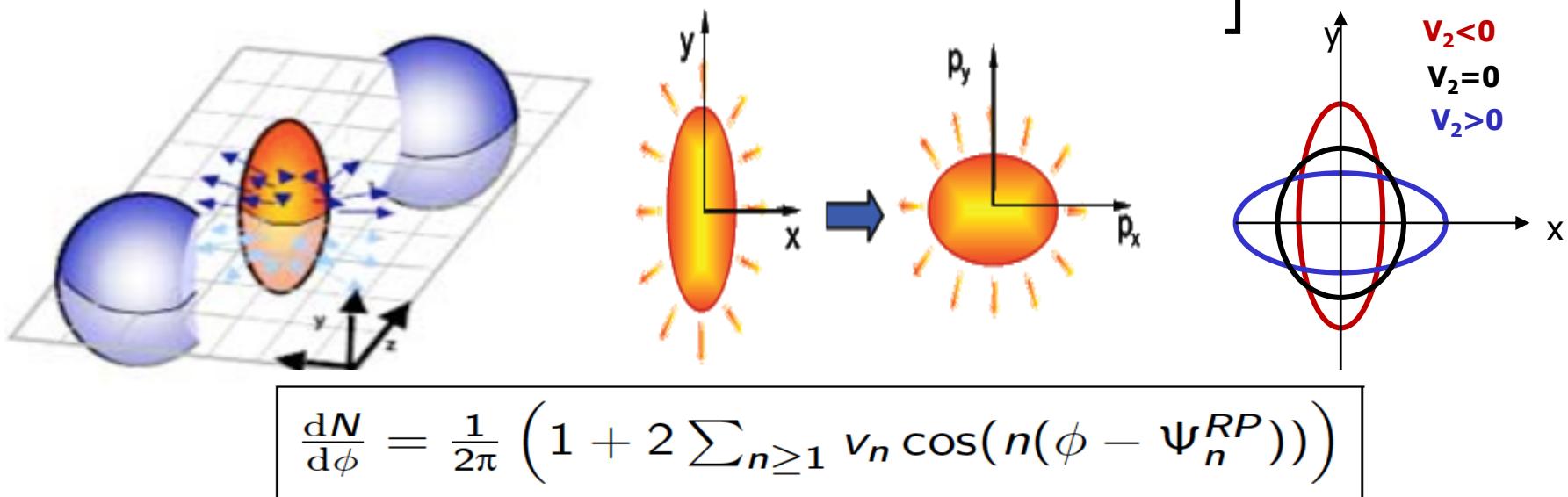


➤ path length dependence of ΔE

- Observable:

$$v_2(p_T) = \langle\langle \cos 2(\phi_{pT} - \psi_{EP}) \rangle\rangle$$

Theoretical Predictions



- Promptly produced EM-interacting particles of $\text{high-}\text{p}_T$ are expected to have no preferred direction w.r.t to the reaction plane, i.e. $v_2 = 0$.

- ✓ $v_2(\gamma) < 0$: jet-medium photons “Fries et al., PRL 90, 132301 (2003)”
- ✓ $v_2(\gamma) = 0$: direct photons “Compton Scattering”
- ✓ $v_2(\gamma) > 0$: frag. photons “Zakharov, JETP Lett. 80, 1 (2004)”

Results – LHC (CMS) – charged hadrons

Nuclear Physics A 904–905 (2013) 459c–462c

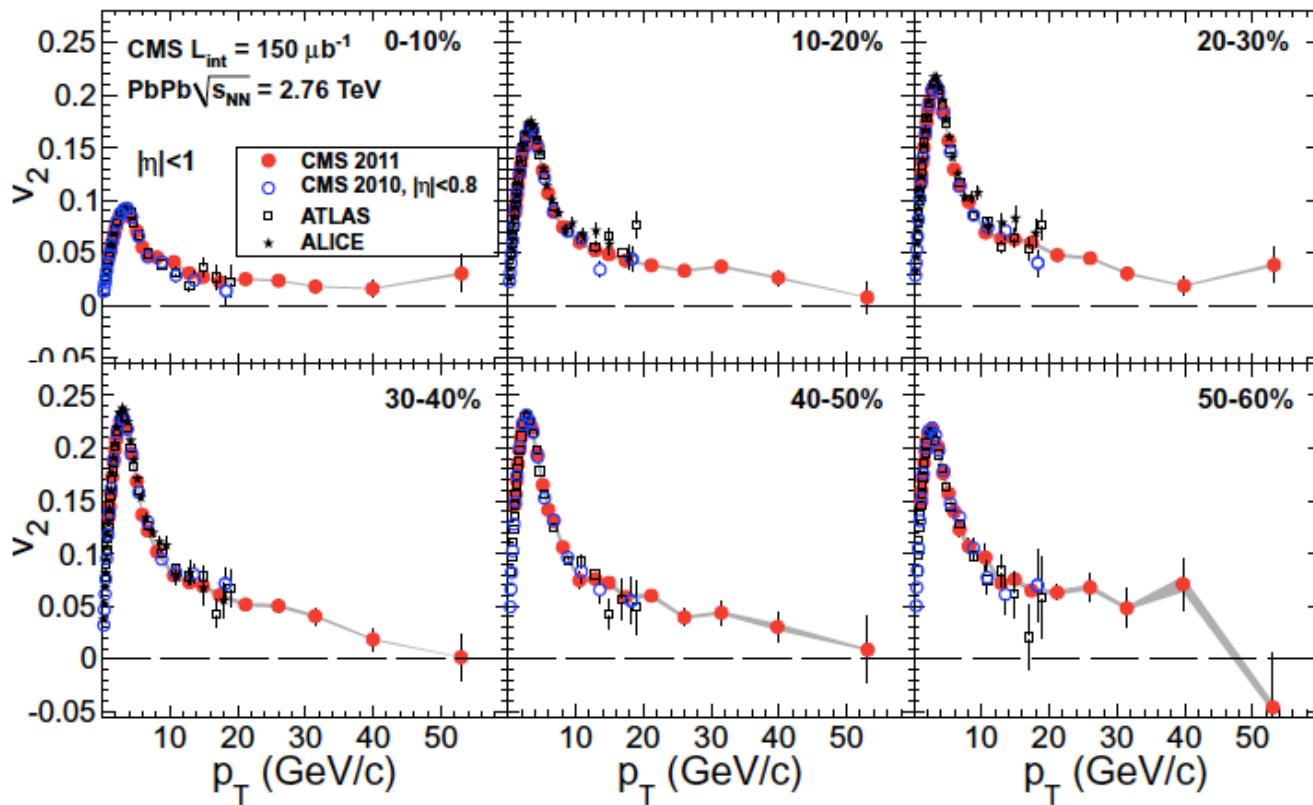


Figure 2: Azimuthal anisotropy, v_2 , as a function of transverse momentum, p_T , of charged hadrons detected by the CMS detector in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in 0 – 60% centrality range for $|\eta| < 1$. Error bars show statistical uncertainties, while the gray bands represent systematic uncertainties.

Results – LHC (ATLAS – CMS - ALICE) – charged hadrons

arXiv:1408.4342v2

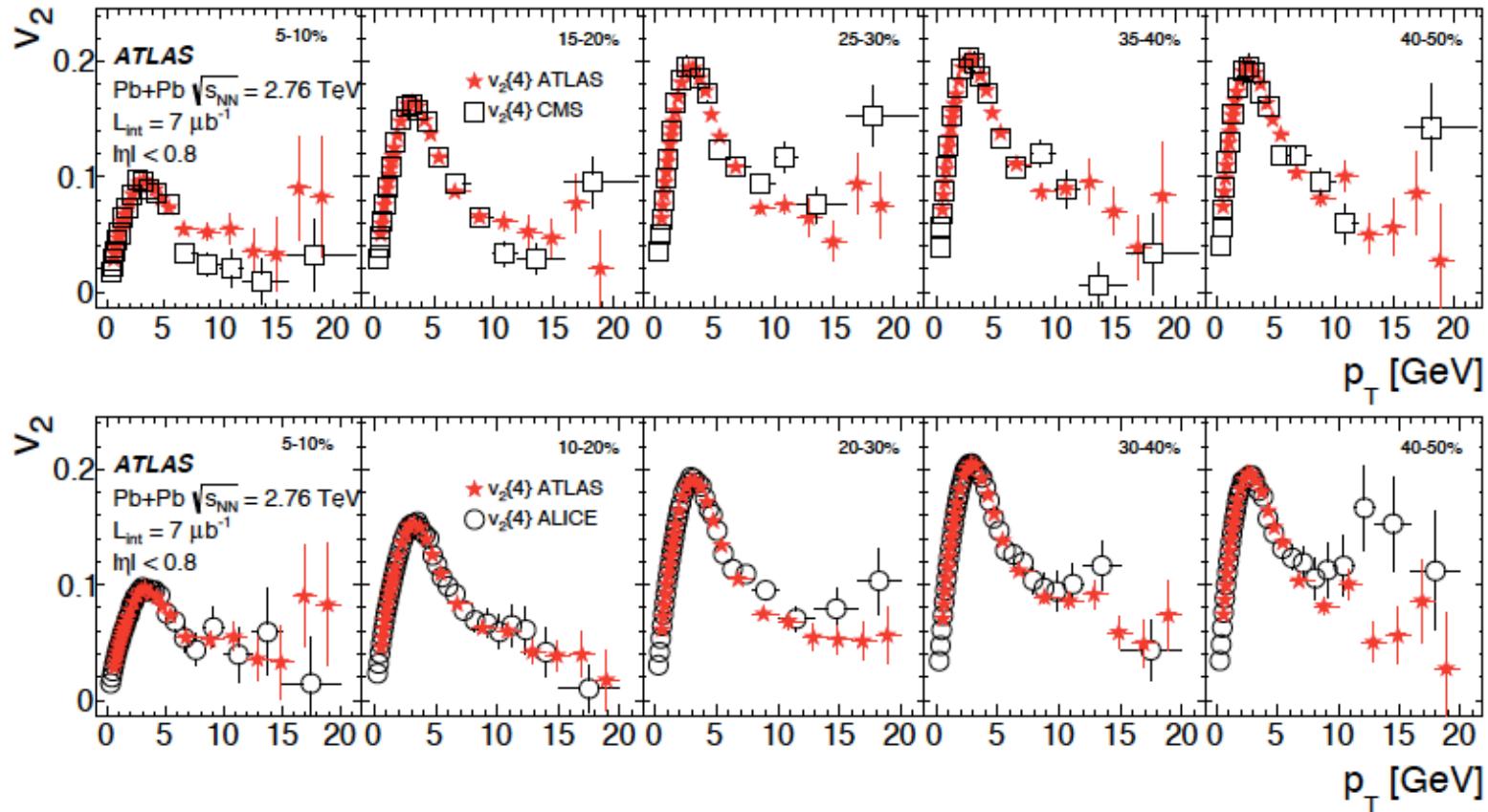


Fig. 4 Comparison of the ATLAS and CMS [20] (top panel), and ATLAS and ALICE [9] (bottom panel) measurements of $v_2\{4\}$ for selected centrality intervals at $|\eta| < 0.8$. The error bars denote statistical and systematic uncertainties added in quadrature.

Results – LHC (ALICE) – Direct Photons

arXiv:1212.3995v2

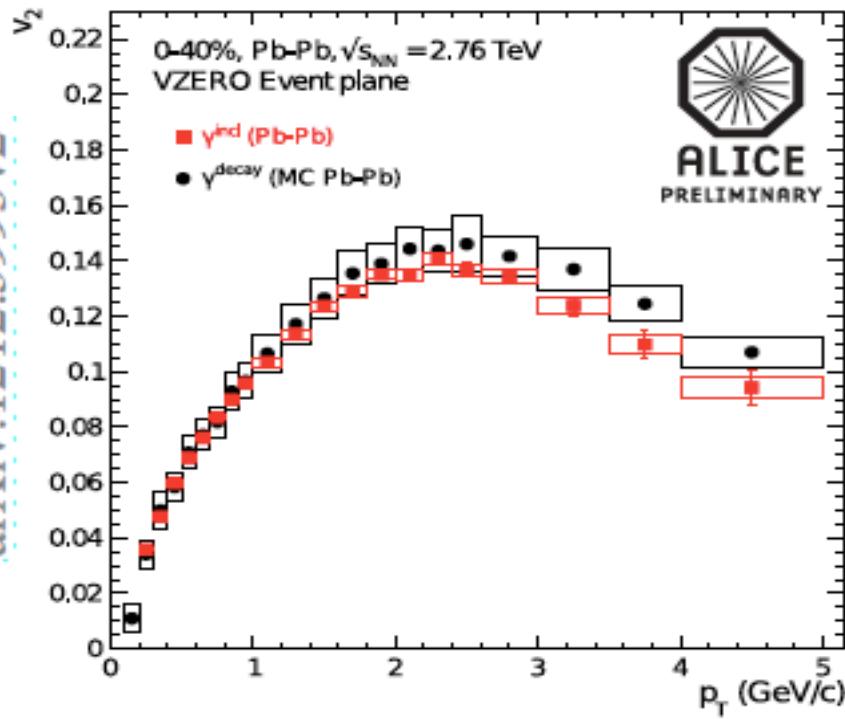


Figure 4: Inclusive photon $v_2^{\gamma, \text{inc}}$ and decay photon $v_2^{\gamma, \text{bg}}$ in 0–40 % Pb-Pb collisions.

$$v_2^{\gamma, \text{direct}} = \frac{R v_2^{\gamma, \text{incl}} - v_2^{\gamma, \text{decay}}}{R - 1}$$

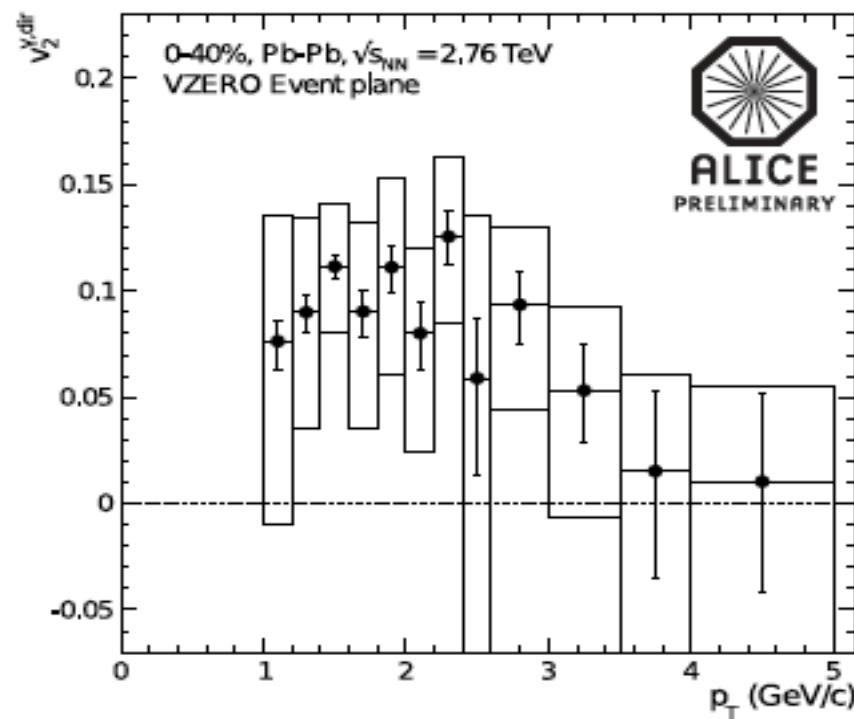
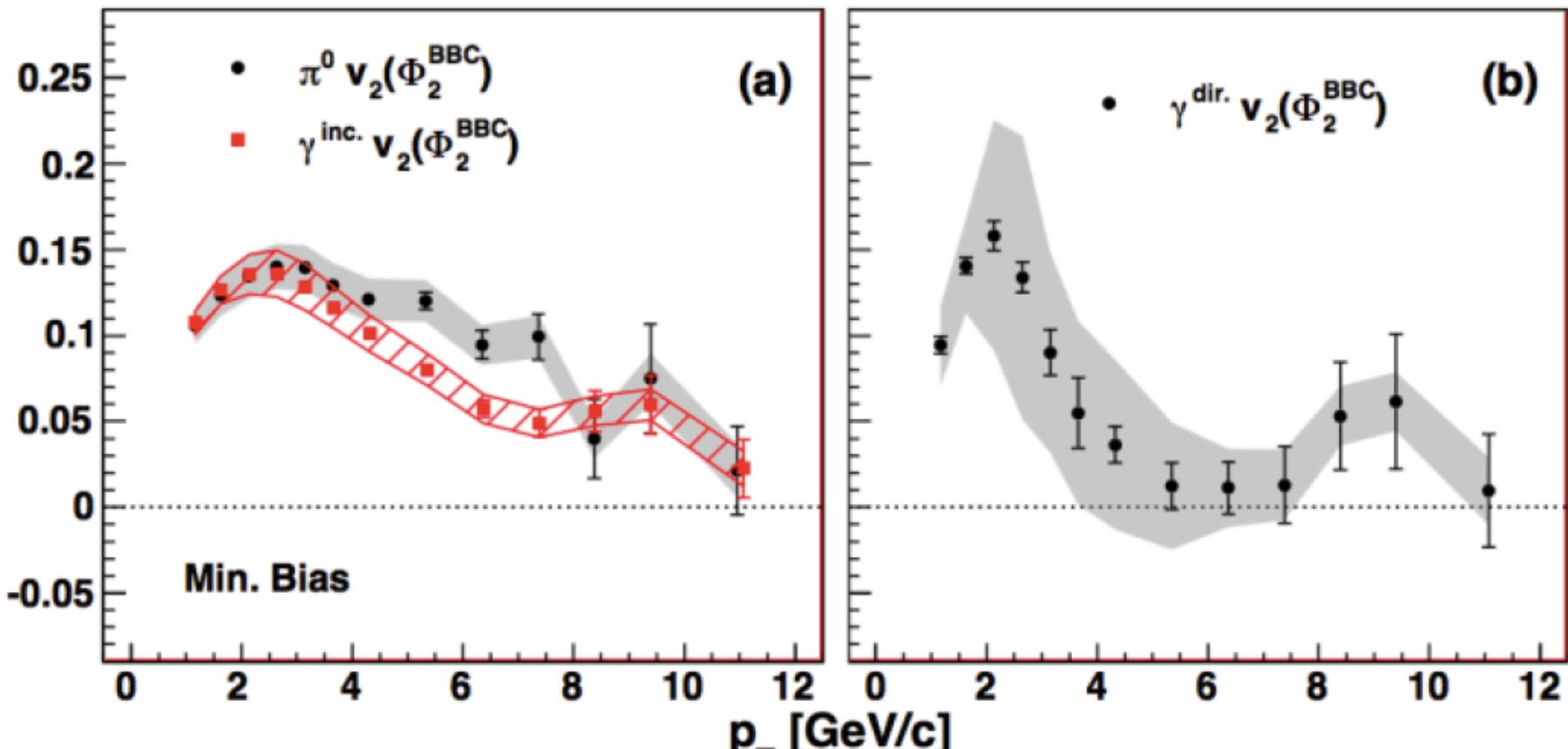


Figure 5: Direct-photon $v_2^{\gamma, \text{dir}}$ in 0–40 % Pb-Pb collisions.

$$\text{with } R = \frac{\gamma^{\text{incl}}}{\gamma^{\text{decay}}} = 1 + \frac{\gamma^{\text{direct}}}{\gamma^{\text{decay}}}$$

Results – RHIC (PHENIX) – Direct Photons

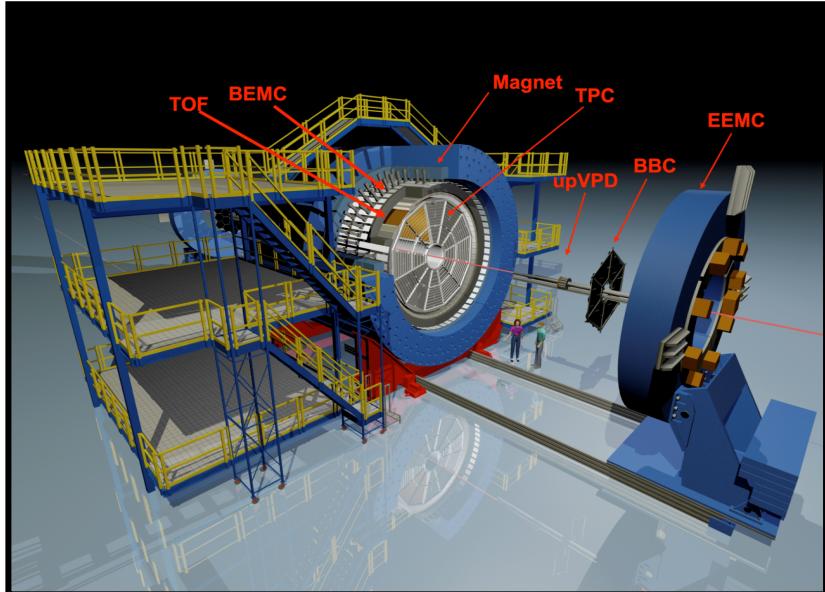
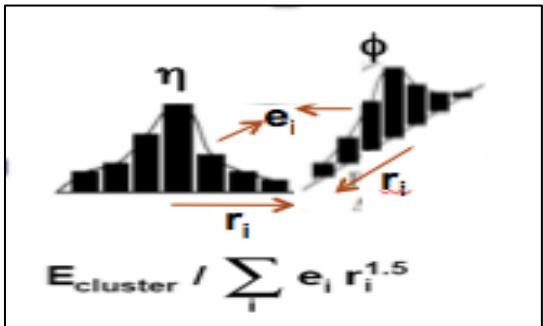
A. Adare et al.: P.R.L. 109, 122302 (2012)



$$v_2^{\text{dir.}} = (R \times v_2^{\text{incl.}} - v_2^{\text{bkgd.}})/(R - 1), \quad R = (\gamma/\pi^0)_{\text{meas}}/(\gamma/\pi^0)_{\text{bkgd}}$$

STAR Techniques (high-p_T direct γ)

- EM neutral cluster identifications
(clustering algo., isolation cut)



- EM transverse shower profile + $Z_{\gamma\gamma}$:
EM neutral energy = π^0 + other sources of EM neutral energy + γ -rich sample

$$v_2^{\gamma_{dir}} = \frac{v_2^{\gamma_{rich}} - \mathcal{R} v_2^{\pi^0_{rich}}}{1 - \mathcal{R}}$$

- ✓ **BEMC:** $|\eta| < 1.0, \Delta\phi = 2\pi$
- ✓ **TPC:** $|\eta| < 1.0, \Delta\phi = 2\pi$
- ✓ **FTPC:** $2.5 < |\eta| < 4.0, \Delta\phi = 2\pi$

$$\mathcal{R} = \frac{N^{bg}}{N^{\gamma_{rich}}} \simeq \frac{N^{\pi^0}}{N^{\gamma_{rich}}}$$

- ✓ π^0 purity, BG assumption justifications

Integrated and Projected Luminosity in STAR

Table 1: Integrated and projected luminosity for γ_{dir} -triggered at $\sqrt{s}=200\text{GeV}$ for different collision systems

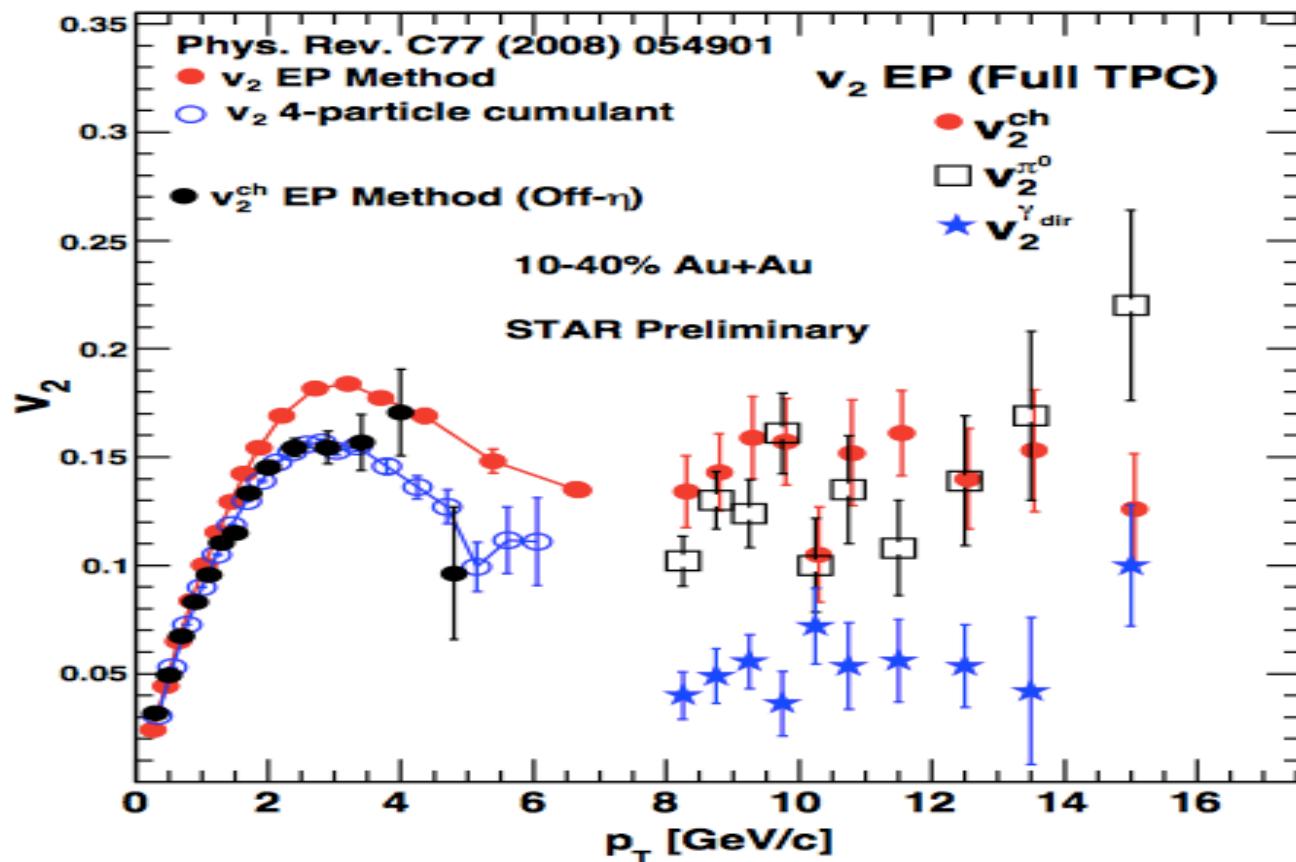
Run	System	Integrated Luminosity	Projected Luminosity	pp-equivalent
6	p+p	9 pb ⁻¹	—	9 pb ⁻¹
7	Au+Au	0.50 nb ⁻¹	—	20 pb ⁻¹
8	d+Au	34 nb ⁻¹	—	13 pb ⁻¹
9	p+p	23 pb ⁻¹	—	23 pb ⁻¹
10	Au+Au	2.0 nb ⁻¹	—	80 pb ⁻¹
11	Au+Au	1.5 nb ⁻¹	—	60 pb ⁻¹
12	p+p	25 pb ⁻¹	—	25 pb ⁻¹
	U+U	0.26 nb ⁻¹	—	—
	Cu+Au	10 nb ⁻¹	—	—
13	Au+Au	0	—	—
	p+p	0	—	—
14	Au+Au	—	9 nb ⁻¹	360 pb ⁻¹
	p+p	—	40 pb ⁻¹	40 pb ⁻¹
15	p+p	—	40 pb ⁻¹	40 pb ⁻¹
16	Au+Au	—	11 nb ⁻¹	440 pb ⁻¹

Current reconstructed data is sufficient

- To measure the v_2 using the STAR forward detector.

Results – RHIC (STAR) – Direct Photons

arXiv: 1008.4894 [nucl-ex]

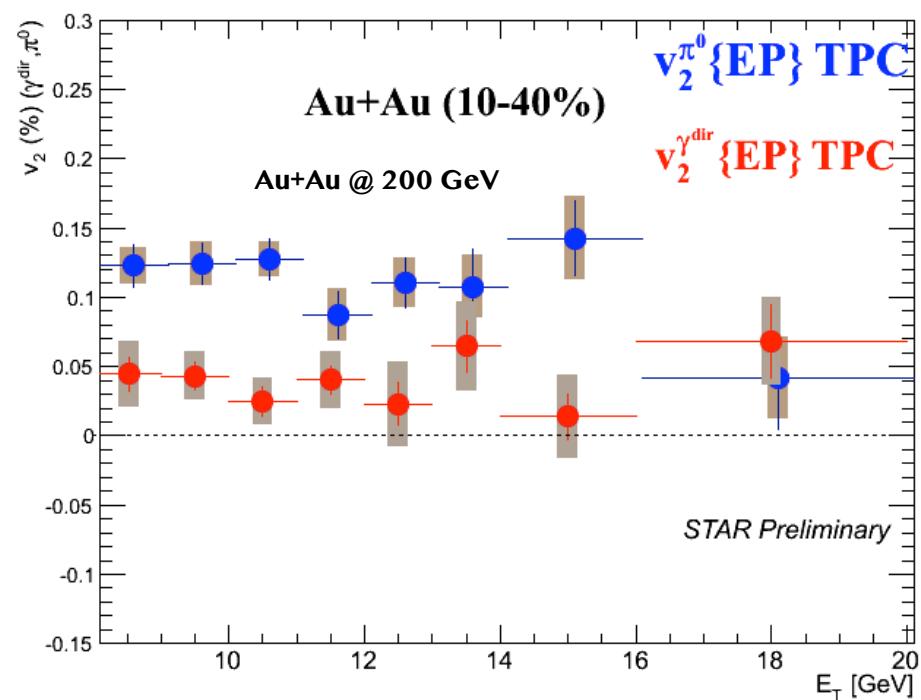


➤ $v_2(\gamma)$ is finite. Event-plane reconstruction biases (non-flow) and/or Frag. photons contributions?

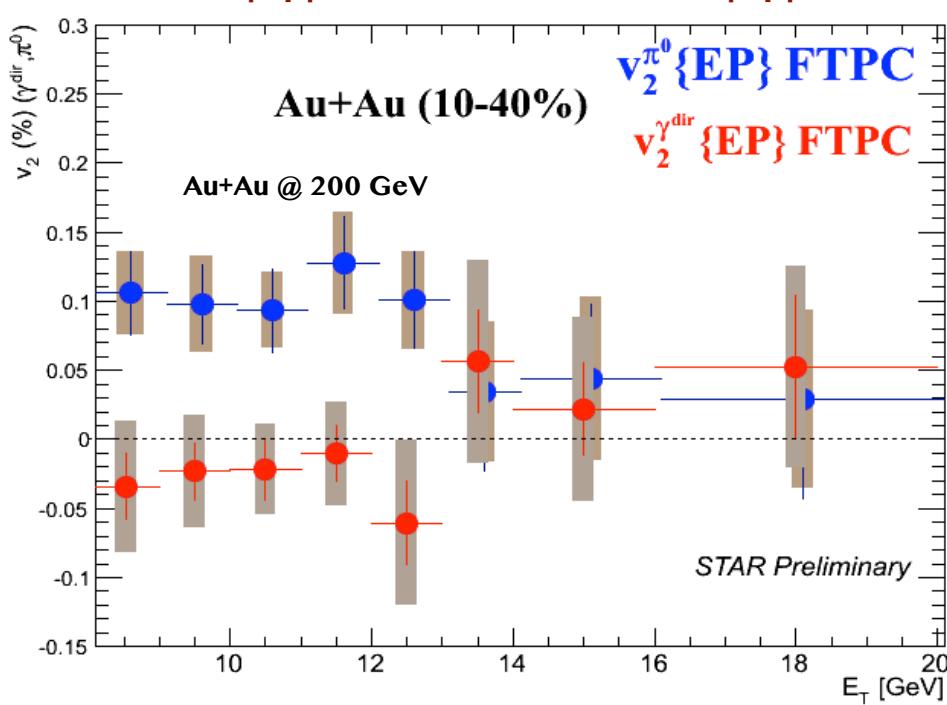
✓ More forward detectors: $2.5 < |\eta| < 4.0$

Results – RHIC (STAR) – Direct Photons

✓ BEMC: $|\eta| < 1.0$, TPC: $|\eta| < 1.0$



✓ BEMC: $|\eta| < 1.0$, FTPC: $2.5 < |\eta| < 4.0$



Nuclear Physics A 931 (2014) 706-711

- v_2 of direct photon is consistent with zero within the current systematic errors
- Remaining bias in reaction-plane determination is small when using forward detector
 - Fragmentation photons have negligible effect on overall v_2 of direct photons
- v_2 of π^0 using the FTPC is apparently due to the path length dependence of energy loss.

✓ $v_2 < 0$: jet-medium photons
✓ $v_2 = 0$: direct photons
✓ $v_2 > 0$: frag. photons

Summary and Outlook

- More differential observables need to be measured in order to better constrain the medium parameters
- ✓ EM probes provide an indispensable information about the medium
- ✓ Azimuthal anisotropy measurements of direct photons act as a unique tool for the path length dependence of parton energy loss in the QGP
- ✓ Different experiment results and very different techniques show a reasonable consistency
- ✓ The high- p_T direct photons ($5 \sim 20$ GeV) is azimuthally uniform distributed w.r.t reaction plane -- $v_2 = 0$
 - ✓ More data to improve stat. and sys. errors.

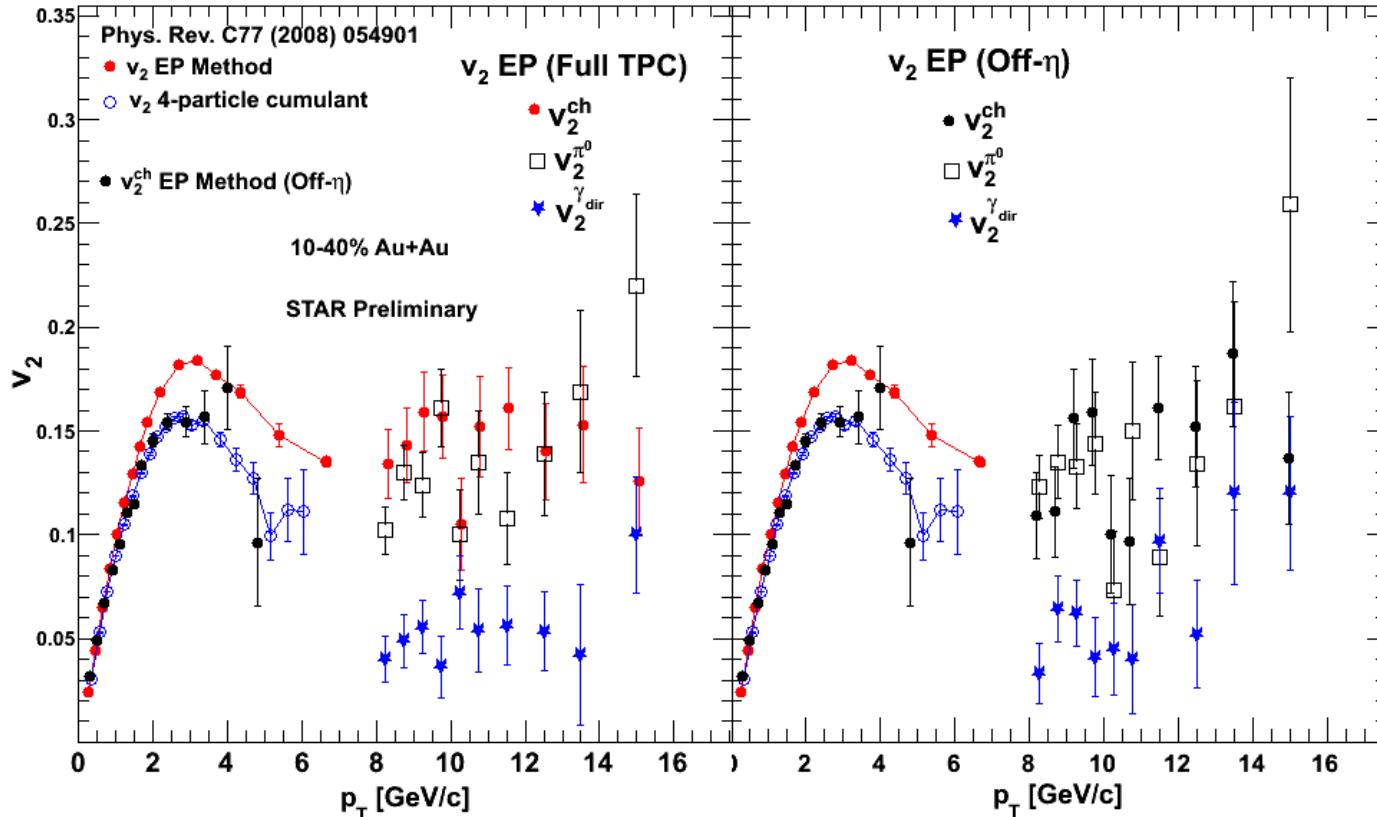


thank you



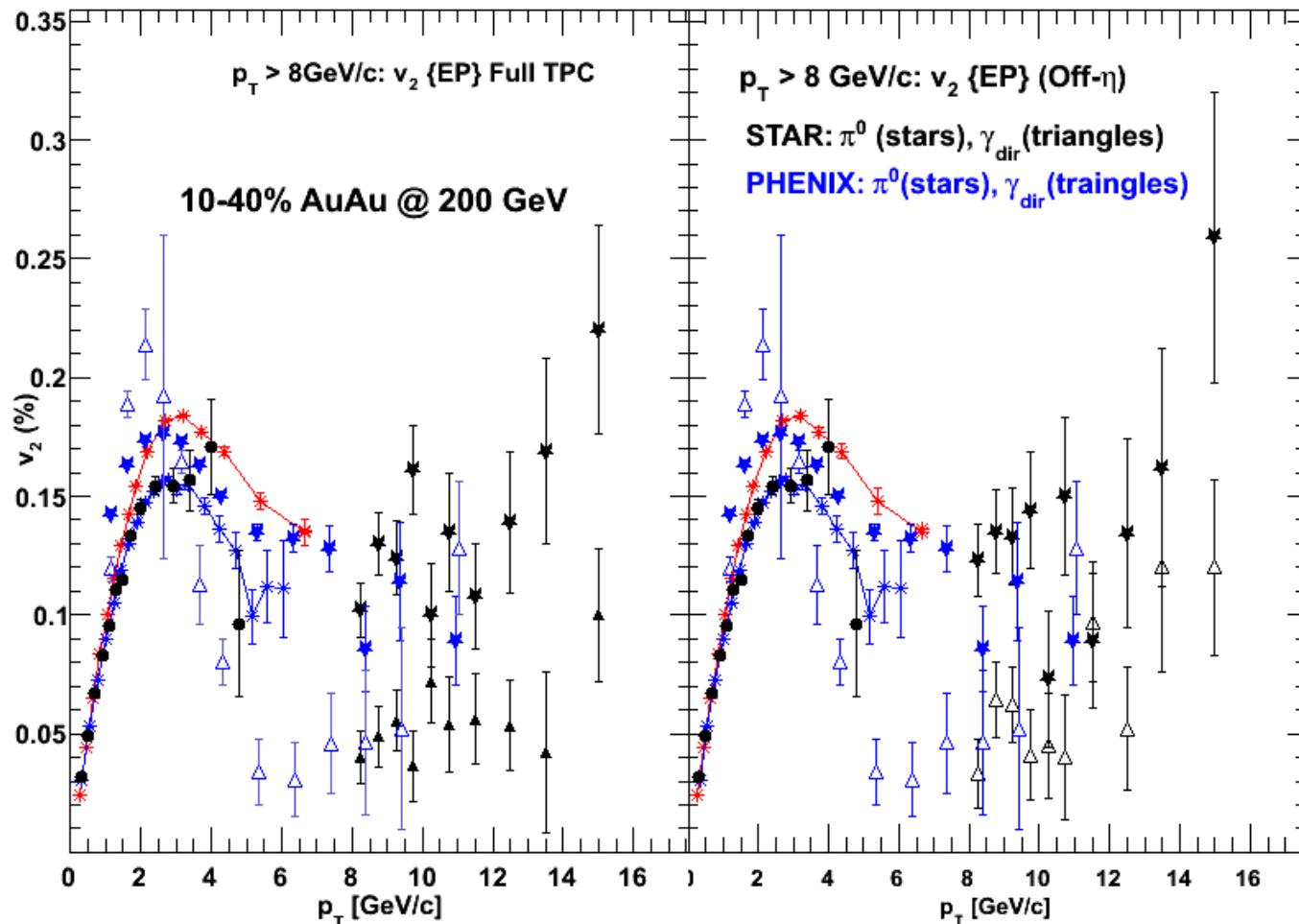
Backup Slides

Previous Results-STAR



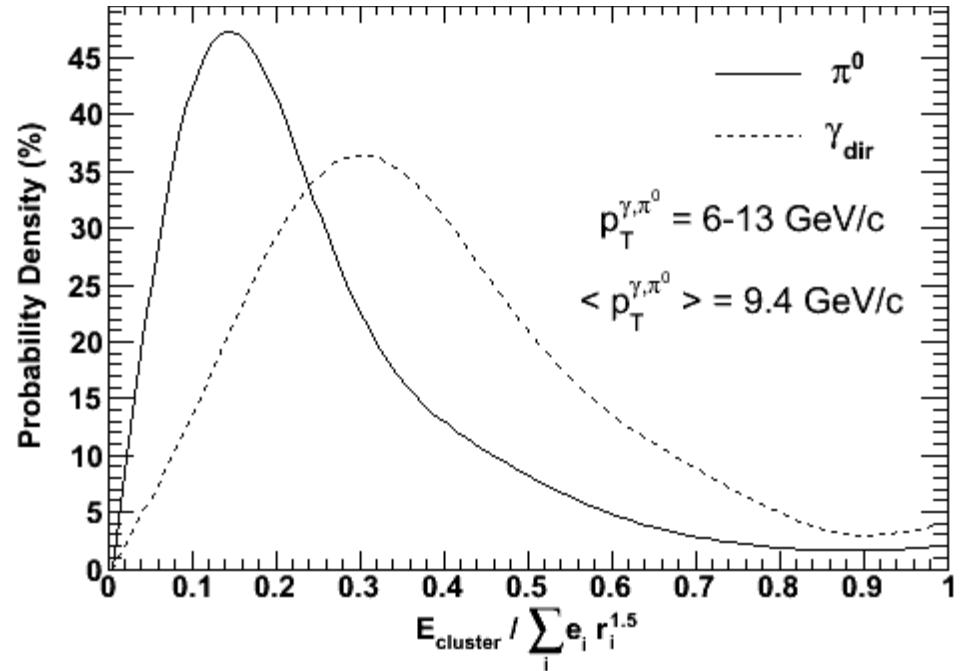
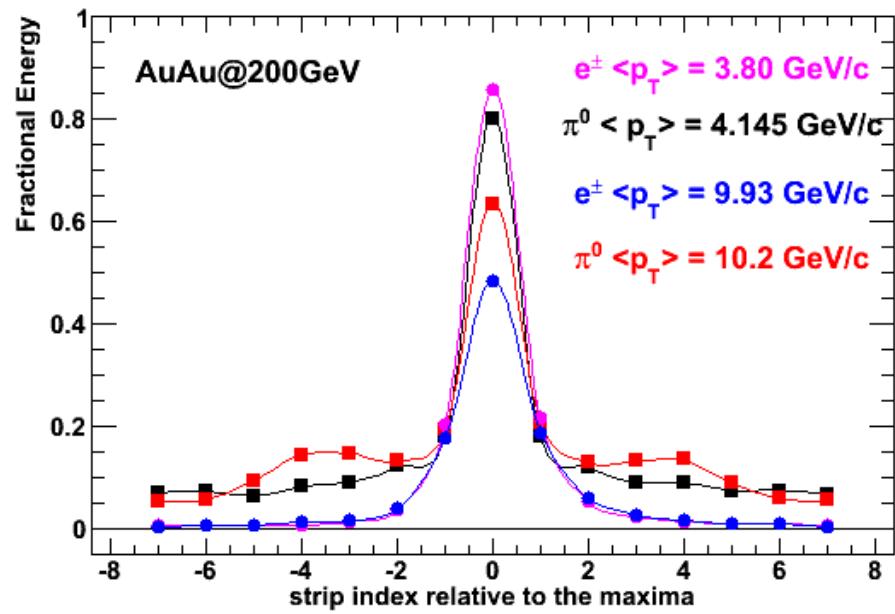
- v_2 of direct photons is $\sim 1/3$ of pions, frag. photons contribution?!
- Not all of the measured v_2 of pions are due to the L dependence of ΔE .

Previous Results-STAR vs. PHENIX



- STAR and PHENIX have similar results using different techniques

EM Transverse Shower Profile



STAR Techniques

- ⊕ Select EM neutral clusters
- ⊕ Use the transverse shower shape to select γ^{dir} free (π^0 -rich) sample and γ^{rich} sample from the neutral clusters.

$$v_2^{\gamma \text{rich}} N^{\gamma \text{rich}} = v_2^{\text{bg}} N^{\text{bg}} + v_2^{\gamma \text{dir}} N^{\gamma \text{dir}}$$

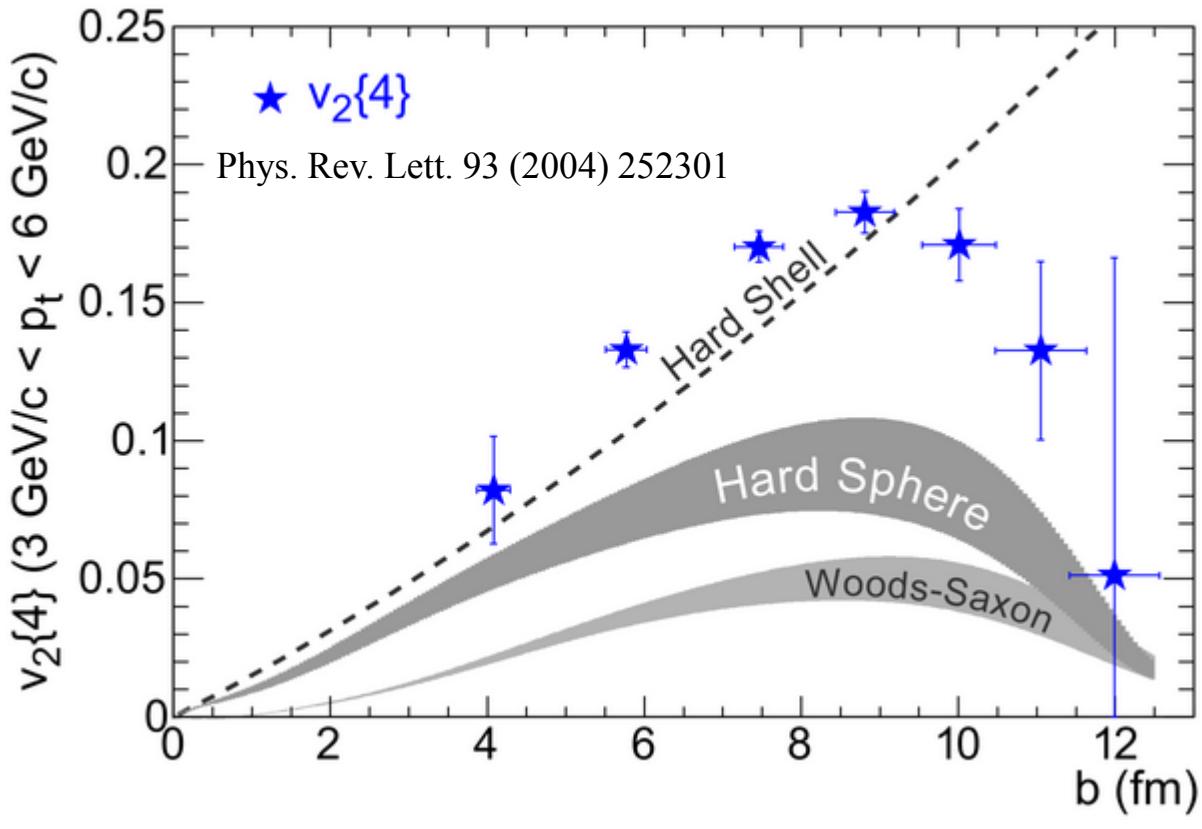
$$\mathcal{R} = \frac{N^{\text{bg}}}{N^{\gamma \text{rich}}} \simeq \frac{N^{\pi^0}}{N^{\gamma \text{rich}}}$$

$$v_2^{\gamma \text{direct}} = \frac{v_2^{\gamma \text{rich}} - v_2^{\text{bg}} \mathcal{R}}{1 - \mathcal{R}}$$

$$v_2^{\gamma \text{direct}} = \frac{v_2^{\gamma \text{rich}} - v_2^{\pi^0} \mathcal{R}}{1 - \mathcal{R}}$$

20

Motivation -II



- v_2 at high p_t seems to be too large for a pure “jet quenching”. Phys. Rev. C 66, 027902(200)
- EM interacting particles of high- p_t are expected to have no preferred direction w.r.t to the reaction plane, i.e. $v_2=0$